




# Accuracy of point-of-care testing devices for haemoglobin in the operating room: meta-analysis

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## Abstract

**Background:** Point-of-care tests (POCT) for haemoglobin are increasingly used to guide intraoperative transfusion. However, their accuracy compared to central laboratory tests is unknown. The objective was to perform a systematic review and meta-analysis of method comparison studies assessing the accuracy of POCT versus central laboratory haemoglobin tests in patients undergoing surgery.

**Methods:** Electronic databases were searched from inception to April 2020 (updated August 2023). Any methodological approach comparing haemoglobin measurements between POCT and central laboratory in patients undergoing surgery under anaesthesia in the operating room were included. Data abstraction was guided by PRISMA and risk of bias was assessed by QUADAS-2. Data were extracted independently and in duplicate by two reviewers. Outcomes included mean differences between POCT and central laboratory haemoglobin with associated standard deviations and 95% limits of agreement (LOA).

**Results:** Of 3057 citations, 34 studies were included ( $n = 2427$ , 6857 paired measurements). Several devices were compared (pulse co-oximetry,  $n = 25$ ; HemoCue,  $n = 10$ ; iSTAT,  $n = 6$ ; blood gas analysers,  $n = 10$ ; haematology analyser,  $n = 2$ ). Median sample size was 41 patients, and 11 studies were funded by device manufacturers. Fifteen of 34 studies had low risk of bias. Pooled mean differences (95% LOA) were: pulse co-oximeters 2.3 g/l (-25.2–29.8), HemoCue -0.3 g/l (-11.1–10.5), iSTAT -0.3 g/l (-8.4–7.8) and blood gas analysers -2.6 g/l (-17.8–12.7).

**Conclusion:** All POCT examining intraoperative haemoglobin measurement yielded pooled mean difference LOAs larger than the allowable limit difference of  $\pm 4$  g/dl. Intraoperative haemoglobin measured by POCT should not be considered interchangeable with central laboratory values and caution is necessary when using these tests to guide intraoperative transfusion.

## Introduction

Red blood cell (RBC) transfusions are common in surgery and may account for 27–44% of all transfused RBC units in the hospital<sup>1</sup>. Transfusions can be life-saving, but also carry risks such as allergic and transfusion reactions, transfusion-associated acute lung injury and transfusion-associated circulatory overload, and have been associated with transfusion-related immunomodulation, which can potentially lead to worse perioperative and long-term oncologic outcomes in surgical patients<sup>2–4</sup>. Lastly, they are an expensive and limited resource, estimated to cost up to €696 per unit<sup>5</sup>.

It is well established that haemoglobin measurement plays a central role in any decision to transfuse RBCs. A recent systematic review of clinical practice guidelines providing transfusion recommendations revealed that of 10 guidelines, eight recommended transfusing based on haemoglobin values<sup>6–9</sup>. A 2016 Cochrane systematic review of studies guiding transfusions identified 31 trials that involved haemoglobin measurements as a trigger for transfusion<sup>10</sup>. Lastly, a recent survey of Canadian

anaesthesiologists reported intraoperative haemoglobin levels to be the most important parameter for transfusion decision-making—more important than blood loss or haemodynamics<sup>11</sup>.

Haemoglobin can be assessed by several methods. Considered to be the gold standard and part of the complete blood count, the haemoglobincyanide (HiCN) method uses an internationally accepted reference calibrator and provides a measured haemoglobin concentration<sup>12</sup>. However, this process is time-consuming and increasingly less useful to guide intraoperative transfusion in the context of acute bleeding. More recently, point-of-care testing devices for haemoglobin (POCT-Hb) have evolved and become the current standard of care during surgery. These devices are relatively simple to use and yield results within seconds to minutes, leading to greater clinical use in the operating room.

There are several classes of POCT-Hb. The first type chemically converts haemoglobin found in the blood sample to azide-haemoglobin, which is then measured by absorption

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photometry. This technology can yield a haemoglobin value from 10  $\mu$ l of whole blood in 10–60 s<sup>13</sup>. A commonly used device in this category is HemoCue (HemoCue AB, Angelholm, Sweden). A second method provides a calculated haemoglobin value based on the conductometric method. Using 65–100  $\mu$ l of whole blood, it calculates haemoglobin in 120 s by multiplying the haematocrit (hct) by a proportionality constant ( $\text{Hb (g/l)} = \text{hct (\%)} \times 3.4$ )<sup>14</sup>. A commonly used device in this category is iSTAT (Abbott Laboratories, Abbott Park, IL, USA). A third common method is pulse oximetry. This technology uses 12 or more wavelengths of light to measure total haemoglobin, and allows for non-invasive continuous monitoring<sup>15</sup>. Devices in this category include Masimo Radical-7 (Masimo Corp., Irvine, CA, USA).

POCT-Hb devices have been validated with static haemoglobin values, such as in healthy blood donors<sup>16–18</sup>, or in non-operative settings, such as the intensive care unit or emergency room<sup>19–21</sup>. The use of POCT-Hb in the intraoperative setting, where haemoglobin levels can change quickly due to bleeding and rapid fluid shifts from concurrent intravenous fluid administration<sup>22</sup>, is relatively untested. There are also few studies assessing POCT-Hb devices within the critical zone of potential transfusion of 60–100 g/l, highlighting a major criticism of existing evaluations<sup>23–25</sup>. The relationship between POCT-Hb and transfusion decisions has been emphasized by multiple other authors<sup>23,26–30</sup>.

Despite the lack of evidence validating their use in the operative setting, POCT-Hb devices have become ubiquitous to guide intraoperative transfusion decisions. The aim of this study is to perform a systematic review and meta-analysis of method comparison studies assessing the accuracy of POCT-Hb compared to central laboratory testing in patients undergoing surgery.

## Methods

### Information sources

This study was registered with PROSPERO (CRD42021233103). Reporting of this review was guided by the PRISMA statement (Table S1).

A systematic search was designed by an information specialist (R.S.). The search included EMBASE (1947 to August 2023), Ovid MEDLINE (1946 to August 2023) and EBM Reviews—Cochrane Central Register of Controlled Trials (August 2023).

### Search strategy

The full electronic search strategy was peer reviewed and conducted following the Peer Review of Electronic Search Strategies (PRESS) guidelines<sup>31</sup>. The search was not limited by language or patient population. Grey literature was included in the form of conference abstracts. References of included articles were reviewed manually for other relevant studies. Finally, the list of included references was circulated to a small group of experts in anaesthesiology and transfusion medicine to identify any additional missing studies. The search strategy is reported in the [Supplementary Methods](#).

### Eligibility criteria

Study participants were required to be patients undergoing any surgery under general or neuraxial anaesthesia in an operating room. Studies that included data from other clinical settings were also included if data provided for the intraoperative period were reported separately. Studies of interest were those

that compared haemoglobin values provided by POCT and the reference central laboratory standard. The gold standard was defined as the HiCN test method with blood samples collected in ethylenediaminetetraacetic acid (EDTA) vacuum collection tubes and processed by a haematology analyser in a central laboratory. POCT devices included any non-invasive measurements via pulse co-oximetry, via occlusion spectroscopy and via transcutaneous reflection. This review also included invasive measurements via absorption photometry, calculations via conductivity or via blood gas analysers. Sampling between the POCT device and central laboratory must have been taken concurrently or analysed from the same sample.

Studies that did not account for within-individual correlation between successive measurements (that is repeated haemoglobin measurements taken from the same patient but analysed as separate data points) were eligible for inclusion, but were accounted for in the analysis. Given differences in transfusion practice, neonatal populations were excluded. Studies that assessed the accuracy of POCT-Hb versus central lab haemoglobin in settings outside the operating room were excluded, such as endoscopy or minor bedside procedures. Finally, studies in which only the haemoglobin mean difference was provided, without the standard deviation (s.d.) or 95% limits of agreement (LOA), were excluded if those values could not be provided by the authors or derived from other data points or graphs.

### Effect measures

The primary outcome was the bias or mean difference (MD) between POCT-Hb minus central lab haemoglobin measurements and its s.d. If not provided in the text, 95% LOA intervals were also calculated using the following formula: 95% LOA = mean difference  $\pm$  1.96  $\times$  s.d.

### Data collection process

Articles identified through the search strategy were imported into Covidence (Covidence, Melbourne, Australia), an online citation manager for systematic reviews<sup>32</sup>. Title, abstract and full-text screening were performed independently and in duplicate by two reviewers (H.A., T.L.). Authors were contacted for any uncertainties regarding eligibility. At both stages of review, any discrepancies were documented, discussed and adjudicated by the senior author (G.M.). Google Translate was used to translate non-English or non-French articles. Reasons for exclusion were documented and reported in the PRISMA flow diagram (Fig. 1).

### Data items

A standard data extraction form was created using Covidence, which was then exported into a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA). Information gathered comprised study characteristics such as year of publication, location, funding source, sample size and study design and patient characteristics including age, sex and weight. Operative characteristics including type of surgery, anaesthesia, duration, blood loss, transfusions, fluid balance and operative interventions were also recorded. Finally, POCT device, central lab analyser, number of paired measurements, timing of samples and sampling site (arterial, venous or capillary) were also documented. Data extraction was performed independently by two reviewers (H.A., T.L.) and authors were contacted for any uncertainties.

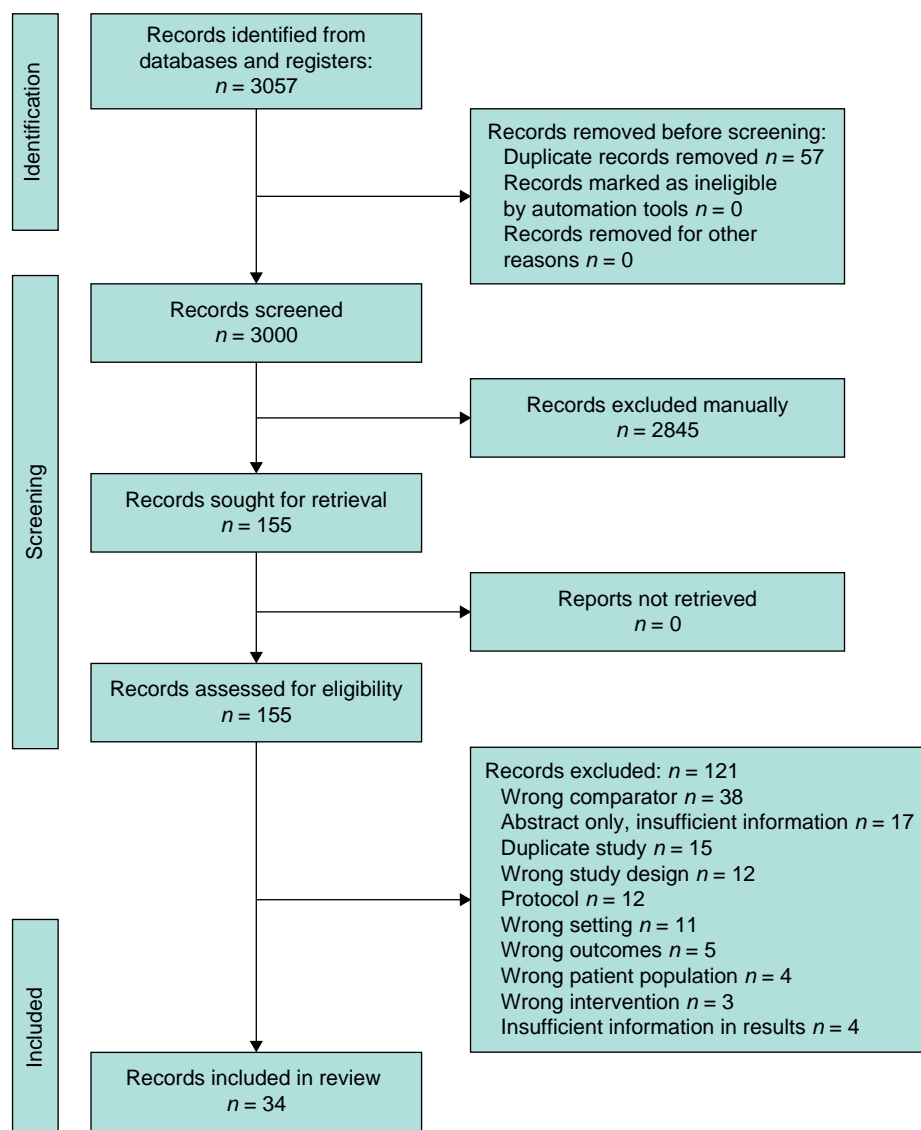


Fig. 1 PRISMA flow diagram

## Statistical analysis

The MD, 95% LOA and s.d. were extracted from each study. Confidence bands of LOA were estimated using a random effects model and robust variance estimation (RVE), as previously described by Williamson *et al.*<sup>33</sup>. For studies that did not account for within-individual correlation for repeated measurements, the s.d. was adjusted to provide an RVE. Confidence bands of LOA are presented by the lower 95% limit for the lower value of the LOA and the upper 95% limit for the upper value of the LOA. The pooled estimate of MD, 95% LOA and confidence bands of LOA were estimated using the approach described by Tipton and Shuster<sup>34</sup>. The correlation coefficient ( $r$ ) and kappa coefficient ( $\kappa$ ) were also extracted. Heterogeneity was determined by the Chi square test (significance level 0.05) combined with the  $I^2$  statistic. Possible sources of heterogeneity were investigated with predefined subgroup analyses including funding source, blood loss, haemoglobin range and sampling site. A sensitivity analysis was performed based on risk of bias. Meta-analysis of each outcome was performed using R (version 4.0.2) in R Studio (version 2022.07.2 build 576), using the base and stats packages<sup>35</sup>.

## Study risk of bias assessment

The quality of included studies was assessed according to the revised Quality Assessment of Diagnostic Studies (QUADAS-2) guidelines<sup>36</sup>. This tool consists of four domains including patient selection, index test, reference standard, and flow and timing. The risk of bias is assessed for each domain in addition to applicability for the first three domains. The questionnaire was adopted from Kim *et al.*<sup>37</sup> and tailored to this review, reported in the [Supplementary Methods](#). If answers to all signalling questions for a domain were 'yes', then risk of bias for that domain was judged low. If two or more domains were deemed 'high' risk of bias, then the overall assessment for the study was judged 'high' risk of bias. Quality assessment was performed by three reviewers (H.A., T.L., R.G.) independently and any disagreements were discussed and adjudicated by the senior author (G.M.).

## Results

### Extent of evidence identified

Results from the search strategy are shown in [Fig. 1](#). A total of 3000 de-duplicated citations were identified for title and abstract

Table 1 QUADAS-2 risk of bias assessment

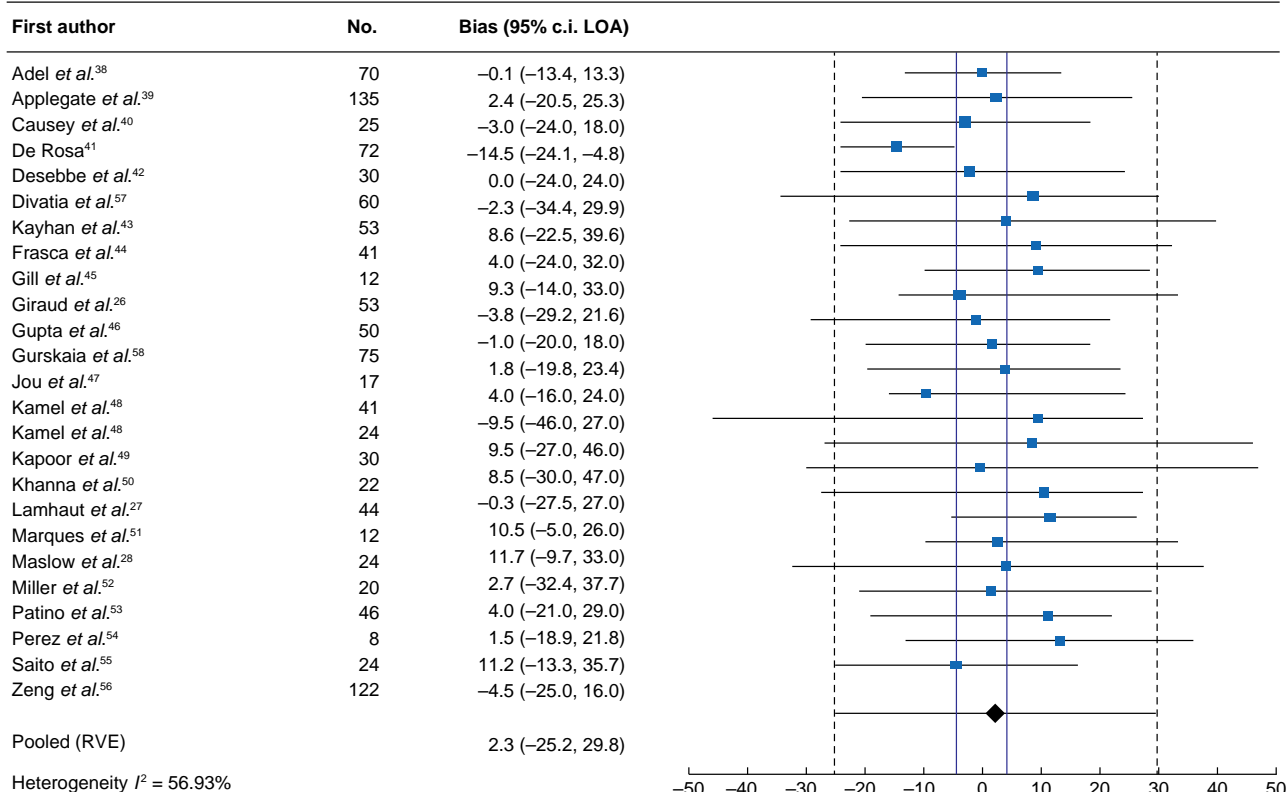
Year	First author	Patient selection	Index test	Reference standard	Flow and timing	Overall
1991	Sfez	High	Low	Low	High	High
1995	McNulty	High	Low	Low	High	High
2000	Despotis	High	Low	Low	High	High
2007	Patel	High	Low	Low	High	High
2008	Steinfeld-Visscher	High	Low	Low	High	High
2009	Perez	High	Low	High	High	High
2010	Jou	High	Low	Low	High	High
2010	Richards	High	Low	High	High	High
2011	Causey	High	Low	High	High	High
2011	Lamhaut	Low	Low	Low	Low	Low
2011	Miller	High	Low	Low	High	High
2011	Spielmann	High	Low	Low	High	High
2012	Gill	High	Low	High	High	High
2013	Giraud	Low	Low	Low	Low	Low
2014	Desebbe	Low	Low	Low	High	Low
2014	Khanna	High	Low	Low	Low	Low
2014	Ng	Low	Low	Low	High	Low
2014	Patino	High	Low	Low	Low	Low
2014	Saito	High	Low	Low	High	High
2015	Carabini	High	Low	Low	Low	Low
2015	Frasca	Low	Low	Low	Low	Low
2015	Marques	High	Low	Low	High	High
2016	Maslow	Low	Low	Low	Low	Low
2016	Zeng	High	High	High	High	High
2017	Erdogan Kayhan	High	Low	Low	Low	Low
2017	Gupta	Low	Low	Low	High	Low
2018	Adel	Low	Low	Low	Low	Low
2018	Kapoor	High	Low	Low	High	High
2019	Applegate	Low	Low	Low	High	Low
2020	De Rosa	Low	Low	Low	High	Low
2020	Divatia	High	High	High	High	High
2020	Kamel	Low	Low	Low	Low	Low
2021	Gurskaia	High	High	High	High	High
2023	Jonsson	High	Low	Low	High	High

Table 2 Meta-analysis of POCT devices and subgroups

Analysis group	Number of studies	Number of patients	Bias (g/l)	Standard deviation of bias	Between-study heterogeneity in bias ( $I^2$ )	95% LOA (g/l)
Pulse Co-Ox	25	1110	2.3	1.15	0.57	(-25.2,29.8)
Pulse Co-Ox (funded)	8	423	2.1	1.17	0.98	(-31.0,35.1)
Pulse Co-Ox (unfunded)	17	687	2.2	1.14	0.18	(-22.1,26.6)
Pulse Co-Ox (blood loss > 1 litre)	5	305	-2.5	0.90	0.80	(-27.9,22.9)
HemoCue	10	525	-0.3	0.48	0.06	(-11.1,10.5)
HemoCue (arterial)	5	314	0.1	0.41	0.07	(-9.6,9.87)
HemoCue (capillary)	5	228	1.4	0.93	0.12	(-18.5,21.2)
HemoCue (venous)	2	90	-1.2	0.51	0.19	(-14.5,12.1)
iSTAT	6	146	-0.3	0.32	0.06	(-8.4,7.8)
Blood gas analyser	10	821	-2.6	0.51	0.32	(-17.8,12.7)
Low risk of bias (Pulse Co-Ox)	13	675	1.9	1.20	0.97	(-29.2,32.9)

POCT, point-of-care tests; LOA, limits of agreement.

## Pulse co-oximeters



**Fig. 2** Forest plot of pulse co-oximeters

Solid vertical red lines indicate allowable difference of  $\pm 4$  g/l defined by the Institute of Quality Management in Healthcare. Haemoglobin units are g/l. LOA, limits of agreement. RVE, robust variance estimation.

review. A total of 155 citations were eligible for full-text review, of which 34 studies were included in the systematic review.

### Characteristics of included studies

Study characteristics are reported in [Table S2](#). Among the included studies, 25 compared pulse co-oximetry devices to central lab ( $n = 1110$  patients, 4059 paired measurements)<sup>26–28,38–58</sup>, nine compared HemoCue ( $n = 525$  patients, 1962 paired measurements)<sup>26,27,39,44,57,59–63</sup>, six compared iSTAT ( $n = 146$  patients, 294 paired measurements)<sup>19,28,40,47,59,64</sup> and 10 compared blood gas analysers ( $n = 821$  patients, 3381 paired measurements)<sup>26,28,39,41,49,50,57,60,63,65</sup>. Two studies compared different POCT haematology analysers ( $n = 295$  patients, 553 paired measurements)<sup>66,67</sup> and were not meta-analysed. There were 27 full-text papers and seven conference abstracts. Median publication date was 2014 (range 1991–2023). Median sample size was 41 (range 6–348). Eleven studies were funded by device manufacturers, one was funded by the U.S. military, three were university-funded, 10 were not funded and 10 did not report funding sources. Participants in 25 studies received a general anaesthetic, one under spinal, and eight were not reported. Eight studies included cardiac surgery, seven neurosurgery, two transplant, two orthopaedic surgery, two gynaecological surgery, two urology, one vascular and 12 were not specified. Nine studies quantified intraoperative blood loss (mean range 100–3400 ml) and three reported blood transfusions (mean range 0–750 ml). Three studies reported mean difference of POCT-Hb devices within the critical transfusion zone of 60–100 g/l.

All included studies reported haemoglobin MD, 28 reported 95% LOA and 17 reported s.d. of the MD. Six studies

accounted for within-individual correlation between successive measurements<sup>26,27,40,52,53,65</sup>.

### Risk of bias assessment

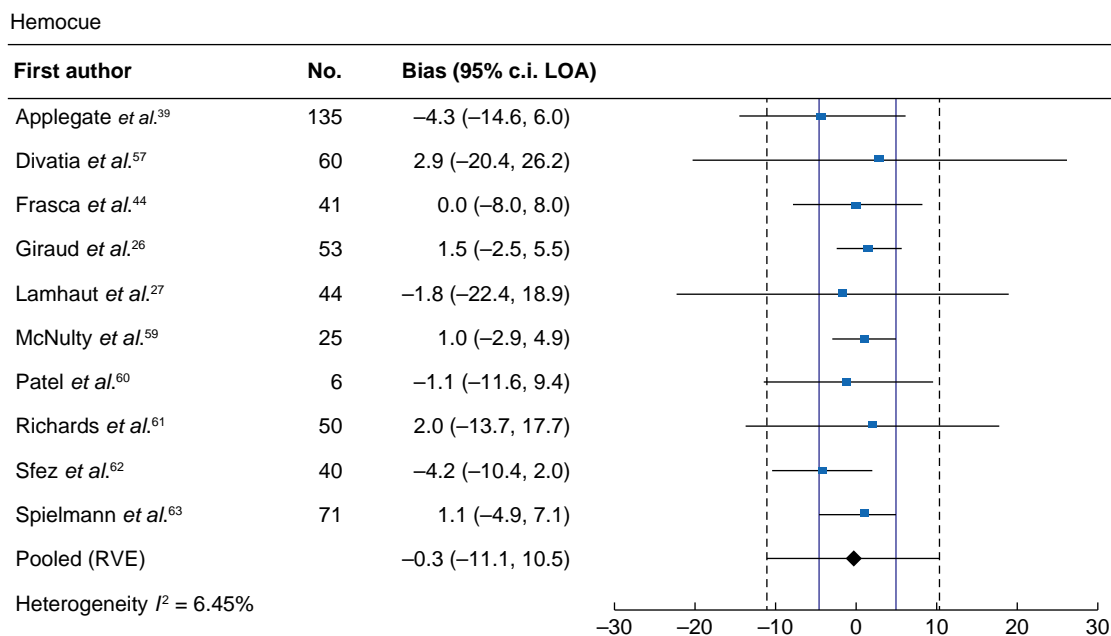
The methodological quality of included studies is shown in [Table 1](#), based on the revised QUADAS-2 guidelines. In total, 15 of 34 studies were assessed to have low risk of bias. Patient selection and flow and timing were assessed to have the highest risk of bias across all studies, while index test and reference standard had the lowest risk. Only six studies reported a sampling method (that is, random, consecutive or convenience sample) and only four papers reported on their types of study design (that is, superiority, equivalence, inferiority).

### Meta-analysis

[Table 2](#) shows the pooled analysis of each class of POCT device and its subgroup analyses. If the included studies had insufficient data to perform subgroup analyses, they were not reported.

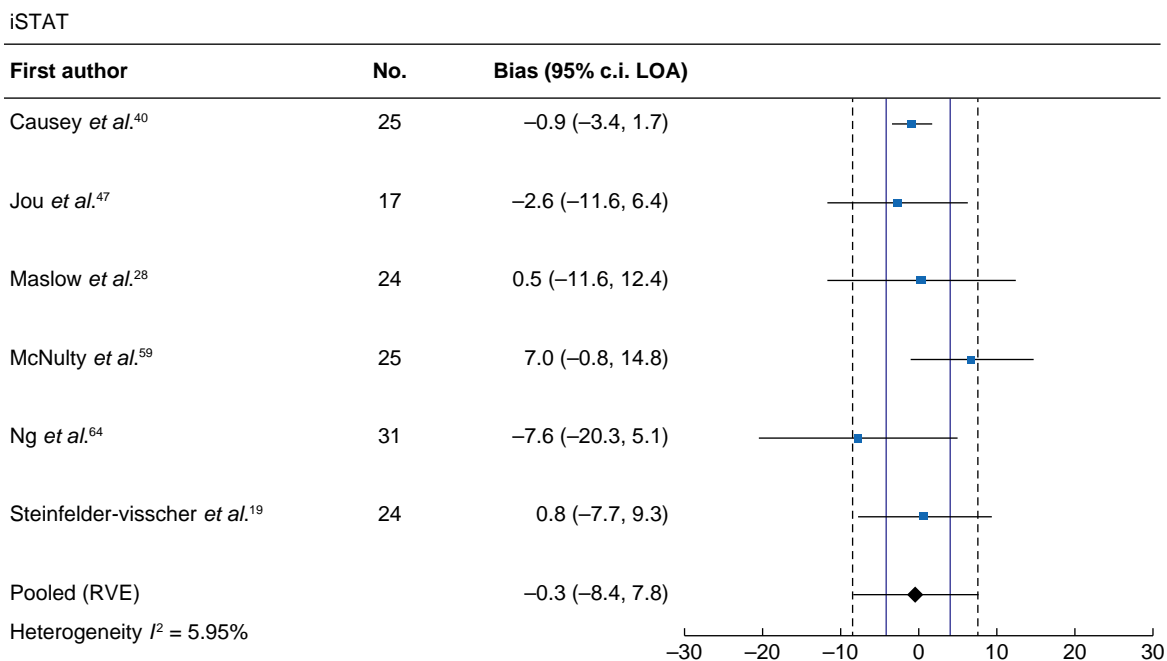
#### Pulse co-oximeter

Meta-analysis of 25 studies assessing pulse co-oximeters revealed an MD (95% LOA) of 2.3 (–25.2 to 29.8) g/l and high heterogeneity ( $I^2 = 57\%$ ; [Fig. 2](#)). When subgroup analyses were performed for industry funding ( $n = 8$ ), non-industry funding ( $n = 15$ ) or blood loss greater than 1 litre ( $n = 5$ ), the MDs (95% LOA) were 2.1 (–31.0 to 35.1) g/l, 2.6 (–25.0 to 30.1) g/l, and –2.5 (–27.9 to 22.9) g/l, respectively. Two studies reported MDs within the critical transfusion zone of 60–100 g/l; thus, a subgroup was not performed. Sensitivity analysis of pulse co-oximetry studies at



**Fig. 3 Forest plot of HemoCue**

Solid vertical red lines indicate allowable difference of  $\pm 4$  g/l defined by the Institute of Quality Management in Healthcare. Haemoglobin units are g/l. LOA, limits of agreement. RVE, robust variance estimation.



**Fig. 4 Forest plot of iSTAT**

Solid vertical red lines indicate allowable difference of  $\pm 4$  g/l defined by the Institute of Quality Management in Healthcare. Haemoglobin units are g/l. LOA, limits of agreement. RVE, robust variance estimation.

low risk of bias ( $n = 12$ ) revealed an MD (95% LOA) of 1.9 (-29.2 to 32.9) g/l (Fig. S1).

### HemoCue

Meta-analysis of 10 studies assessing HemoCue revealed an MD (95% LOA) of -0.3 (-11.1 to 10.5) g/l and low heterogeneity ( $I^2 = 6\%$ ; Fig. 3). Subgroup analyses of arterial, capillary and venous samples demonstrated MDs (95% LOA) of 0.1 (-9.6 to 9.8) g/l, 1.4 (-18.5 to 21.2) g/l and -1.2 (-14.5 to 12.1) g/l, respectively.

### iSTAT

Meta-analysis of six studies assessing iSTAT revealed an MD (95% LOA) of -0.3 (-8.4 to 7.8) g/l and low heterogeneity ( $I^2 = 6\%$ ; Fig. 4).

### Blood gas analysers

Meta-analysis of 10 studies assessing blood gas analysers revealed an MD (95% LOA) of -2.6 (-17.8 to 12.7) g/l and low heterogeneity ( $I^2 = 32\%$ ; Fig. S2).

## Discussion

In this systematic review, the accuracy of point-of-care haemoglobin devices compared to central laboratory measurements in patients undergoing surgery was assessed. Most studies compared pulse co-oximetry to central laboratory measurements, with fewer studies examining HemoCue, iSTAT and blood gas analysers. Of the 34 included studies, none examined occlusion spectroscopy or transcutaneous reflection spectroscopy. Almost a third of studies were industry-funded and only a minority quantified blood loss. Only three studies compared devices within the critical transfusion zone of 60–100 g/l. Overall, the accuracies of the reported devices are inadequate to guide intraoperative transfusion decision-making. The sample size and number of available studies for each POCT device were low and further high-quality prospective accuracy studies are warranted.

To the authors' knowledge, this is the first systematic review and meta-analysis that investigates method comparison studies of POCT devices versus central laboratory haemoglobin measurements specifically in the operative setting. Given that haemoglobin values play a central role in transfusion decision-making in surgery, it is imperative to evaluate the accuracy of POCT devices as they are increasingly used in lieu of formal central laboratory assays. The current analyses demonstrate that the pooled bias (g/l) of pulse co-oximetry, HemoCue, iSTAT and blood gas analysers was 2.3, –0.3, –0.3 and –2.6, respectively. The bias indicates the difference of the mean error above and below the reference measurement but does not report the magnitude of the error in each direction. Thus, clinically, the bias alone would be insufficient to compare methods. Rather, the 95% LOAs provide the interval within which 95% of the differences between haemoglobin measurements by the two methods are expected to lie<sup>68,69</sup>. In this context, the 95% LOA is more clinically relevant to assess agreement between methods. The pooled 95% LOA (g/l) for pulse co-oximeters, HemoCue, iSTAT and blood gas analysers were –25.2 to 29.8, –11.1 to 10.5, –8.4 to 7.8 and –17.8 to 12.7, respectively. These intervals are much larger than the allowable difference of  $\pm 4$  g/l defined by the Institute of Quality Management in Healthcare (IQMH)<sup>70</sup>. Alternatively, when using an allowable difference of  $\pm 10$  g/l, as previously argued by Morey and colleagues<sup>24</sup>, the 95% LOA of iSTAT falls within this range; however, only six studies ( $n = 146$  patients) were included in this meta-analysis, of which four had high risks of bias. As such, haemoglobin values measured by POCT devices should not be considered interchangeable with central laboratory values and abundant caution is needed when using these devices to guide transfusion decisions in the operating room.

Other systematic reviews and meta analyses of the accuracy of POCT devices measuring haemoglobin have been reported<sup>21,37,71,72</sup>, but all have significant differences compared to this review. Shabaninejad and colleagues<sup>71</sup> included 28 studies comparing Radical-7 pulse co-oximetry to central laboratory measurements in the operative setting and demonstrated a bias (95% LOA) of 2.7 (–4.4 to –1.0) g/l. However, their meta-analysis included other POCT devices such as iSTAT and blood gas analysers as reference measurements. The accuracy of these devices has not been validated for use in surgery and therefore these were not considered an acceptable reference comparator in the current review. Further, Shabaninejad et al.'s review was limited to Radical-7 pulse co-oximetry, and sensitivity analyses based on study quality and risk of bias were not presented. In 2020, Zortea

and colleagues<sup>72</sup> included eight studies comparing haemoglobin values measured by non-invasive techniques versus central laboratory. Their sensitivity analysis of surgical patients in four studies revealed a mean overall difference of 0.02 (95% c.i. –0.43 to 0.47). However, this group included patients outside of the operative setting and used POCT devices such as blood gas analysers as reference standards. In 2015, Hiscock and colleagues<sup>21</sup> published a meta-analysis of 39 studies comparing pulse co-oximetry and HemoCue to central laboratory haemoglobin measurements and reported a bias (95% LOA) of –0.3 (–30 to 29 g/l) and 0.8 (–13 to 14 g/l), respectively. Their results demonstrate that Masimo pulse co-oximetry devices have lower precision and wider 95% LOA compared to HemoCue, which is consistent with the current analysis; however, their review included primarily non-operative data. Further, Kim and colleagues<sup>37</sup> analysed 32 studies comparing non-invasive haemoglobin measurements (Masimo, OrSense) to central laboratory testing. More specifically, a subgroup analysis of 13 studies conducted in the perioperative setting demonstrated a bias (95% LOA) of 3.9 (–22.1 to 29.8 g/l). Again, this subgroup included patients outside of the operative setting. Lastly, none of the other reviews addressed within-individual correlation between successive measurements. In the current paper, six studies reported repeated measures. For the remaining 26 studies, the standard deviation was adjusted to provide a robust variance estimation.

The current review has several limitations. Results should be interpreted carefully as 18 of 34 studies were assessed to have high overall risk of bias. It is also noteworthy that 11 studies were funded by device manufacturers. The accuracy of the POCT device may be overestimated as industry-funded studies that show a larger difference between the POCT device and the central laboratory may be less likely to be published. In addition, a high level of heterogeneity was identified in the pulse co-oximetry group, likely owing in part to different operation types, blood loss, and intraoperative interventions such as cardiopulmonary bypass and acute normovolaemic haemodilution, which may affect haemoglobin measurements. Only three studies reported blood transfusions<sup>41,46,55</sup>. In the study of De Rosa, transfusion was performed if haemoglobin was  $< 80$  g/l in healthy patients or  $< 90$  g/l in patients with cardiac disease or active bleeding. In Gupta et al., blood transfusion was at the discretion of the anaesthesiologist and parameters were not specified. No patients received allogeneic blood transfusions in Saito et al.

Intraoperative decision-making for RBC transfusions is complex and is not based on a robust evidence base. A 2021 systematic review of clinical practice guidelines for intraoperative RBC transfusions identified 10 guidelines<sup>73</sup>. However, recommendations were highly variable and data were extrapolated from non-operative settings. Further, none provided recommendations on the most appropriate method for haemoglobin measurement, although all implied that transfusions should be guided at least in part by haemoglobin/haematocrit triggers, thresholds and/or targets. No guideline discussed the role of point-of-care haemoglobin testing.

This review suggests that POCT haemoglobin devices are insufficiently accurate to be used interchangeably with central laboratory haemoglobin testing in the operating room. This finding is particularly important as it pertains to transfusion decision-making, and inaccurate haemoglobin measurements could lead to over- or under-transfusion, both of which can lead to significant patient harm. Further prospective accuracy data are required to compare the accuracy of POCT haemoglobin

devices in the operative setting, principally within the critical transfusion zone of 60–100 g/l, as well as to determine their ability to appropriately guide transfusion.

## Funding

No specific funding was received for this project.

## Disclosure

The authors declare no conflicts of interest.

## Supplementary material

Supplementary material is available at BJS Open online.

## Data availability

The authors declare that the data supporting the findings of this study are available within the article and its supplementary files.

## References

- Shehata N, Forster A, Lawrence N, Rothwell DM, Fergusson D, Tinmouth A et al. Changing trends in blood transfusion: an analysis of 244,013 hospitalizations. *Transfusion* 2014;**54**: 2631–2639
- Madjdpour C, Spahn DR. Allogeneic red blood cell transfusions: efficacy, risks, alternatives and indications. *Br J Anaesth* 2005;**95**: 33–42
- Vamvakas EC, Blajchman MA. Transfusion-related immunomodulation (TRIM): an update. *Blood Rev* 2007;**21**: 327–348
- Whitson BA, Huddleston SJ, Savik K, Shumway SJ. Risk of adverse outcomes associated with blood transfusion after cardiac surgery depends on the amount of transfusion. *J Surg Res* 2010;**158**:20–27
- Shander A, Hofmann A, Gombotz H, Theusinger OM, Spahn DR. Estimating the cost of blood: past, present, and future directions. *Best Pract Res Clin Anaesthesiol* 2007;**21**:271–289
- Baker L, Park L, Gilbert R, Ahn H, Martel A, Davies A et al. Guidelines on the intraoperative transfusion of red blood cells: a systematic review. *BMJ Open* 2019;**9**:e029684
- Turgeon AF, Fergusson DA, Doucette S, Khanna MP, Tinmouth A, Aziz A et al. Red blood cell transfusion practices amongst Canadian anesthesiologists: a survey. *Can J Anaesth* 2006;**53**: 344–352
- Brunskill SJ, Millette SL, Shokoohi A, Pulford EC, Doree C, Murphy MF et al. Red blood cell transfusion for people undergoing hip fracture surgery. *Cochrane Database Syst Rev* 2015;**4**:CD009699
- Wilkinson KL, Brunskill SJ, Doree C, Trivella M, Gill R, Murphy MF. Red cell transfusion management for patients undergoing cardiac surgery for congenital heart disease. *Cochrane Database Syst Rev* 2014;**2**:CD009752
- Carson JL, Stanworth SJ, Roubinian N, Fergusson DA, Trulzi D, Doree C et al. Transfusion thresholds and other strategies for guiding allogeneic red blood cell transfusion. *Cochrane Database Syst Rev* 2016;**10**:CD002042
- Bennett S, Ayoub A, Tran A, English S, Tinmouth A, McIsaac DI et al. Current practices in perioperative blood management for patients undergoing liver resection: a survey of surgeons and anesthesiologists. *Transfusion* 2018;**58**:781–787
- Shah VB, Shah BS, Puranik GV. Evaluation of non cyanide methods for hemoglobin estimation. *Indian J Pathol Microbiol* 2011;**54**:764–768
- Sanchis-Gomar F, Cortell-Ballester J, Pareja-Galeano H, Banfi G, Lippi G. Hemoglobin point-of-care testing: the HemoCue system. *J Lab Autom* 2013;**18**:198–205
- Papadea C, Foster J, Grant S, Ballard SA, Cate JC, Southgate WM et al. Evaluation of the i-STAT portable clinical analyzer for point-of-care blood testing in the intensive care units of a university children's hospital. *Ann Clin Lab Sci* 2002;**32**:231–243
- Cannesson M, Talke P. Recent advances in pulse oximetry. *F1000 Med Rep* 2009;**1**:66
- Baart AM, de Kort WLAM, van den Hurk K, Pasker-de Jong PCM. Hemoglobin assessment: precision and practicability evaluated in the Netherlands—the HAPPEN study. *Transfusion* 2016;**56**:1984–1993
- Bahadur S, Jain S, Jain M. Estimation of hemoglobin in blood donors: a comparative study using HemoCue and cell counter. *Transfus Apher Sci* 2010;**43**:155–157
- Radtke H, Polat G, Kalus U, Salama A, Kiesewetter H. Hemoglobin screening in prospective blood donors: comparison of different blood samples and different quantitative methods. *Transfus Apher Sci* 2005;**33**:31–35
- Steinfeldt-Visscher J, Teerenstra S, Gunnewiek JMTK, Weerwind PW. Evaluation of the i-STAT point-of-care analyzer in critically ill adult patients. *J Extra Corpor Technol* 2008;**40**:57–60
- Dolscheid-Pommerich RC, Dolscheid S, Grigutsch D, Stoffel-Wagner B, Graeff I. Comparability of point-of-care versus central laboratory hemoglobin determination in emergency patients at a supra-maximal care hospital. *PLoS One* 2016;**11**:e0166521
- Hiscock R, Simmons S, Carstensen B, Gurrin L. Comparison of Massimo Pronto-7 and HemoCue Hb 201+ with laboratory haemoglobin estimation: a clinical study. *Anaesth Intensive Care* 2014;**42**:608–613
- Wu P, Morey TE, Harris NS, Gravenstein N, Rice MJ. Intravenous fluids cause systemic bias in a conductivity-based point-of-care hematocrit meter. *Anesth Analg* 2012;**114**:314–321
- Johnson M, Marwick PC, Coetzee JF. Comparison of hemoglobin measurements by 3 point-of-care devices with standard laboratory values and reliability regarding decisions for blood transfusion. *Anesth Analg* 2019;**131**:640–649
- Morey TE, Gravenstein N, Rice MJ. Let's think clinically instead of mathematically about device accuracy. *Anesth Analg* 2011;**113**:89–91
- Rice MJ, Gravenstein N, Morey TE. Noninvasive hemoglobin monitoring: how accurate is enough? *Anesth Analg* 2013;**117**: 902–907
- Giraud B, Frasca D, Debaene B, Mimoz O. Comparison of haemoglobin measurement methods in the operating theatre. *Br J Anaesth* 2013;**111**:946–954
- Lamhaut L, Apriotesei R, Combes X, Lejay M, Carli P, Vivien B. Comparison of the accuracy of noninvasive hemoglobin monitoring by spectrophotometry (SpHb) and HemoCue® with automated laboratory hemoglobin measurement. *Anesthesiology* 2011;**115**:548–554
- Maslow A, Bert A, Singh A, Sweeney J. Point-of-care hemoglobin/hematocrit testing: comparison of methodology and technology. *J Cardiothorac Vasc Anesth* 2016;**30**:352–362



29. Morey TE, Gravenstein N, Rice MJ. Assessing point-of-care hemoglobin measurement: be careful we don't bias with bias. *Anesth Analg* 2011;**113**:1289–1291
30. Broderick AJ. Point-of-care haemoglobin measurement—state of the art or a bleeding nuisance? *Anaesthesia* 2015;**70**:1225–1229
31. McGowan J, Sampson M, Salzwedel DM, Cogo E, Foerster V, Lefebvre C. PRESS Peer Review of Electronic Search Strategies: 2015 guideline statement. *J Clin Epidemiol* 2016;**75**:40–46
32. *Covidence Systematic Review Software*. Melbourne, Australia: Veritas Health Innovation; Available from: [www.covidence.org](http://www.covidence.org)
33. Williamson PR, Lancaster GA, Craig JV, Smyth RL. Meta-analysis of method comparison studies. *Stat Med* 2002;**21**:2013–2025
34. Tipton E, Shuster J. A framework for the meta-analysis of Bland–Altman studies based on a limits of agreement approach. *Stat Med* 2017;**36**:3621–3635
35. R Core Team. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing; Available from: <https://www.R-project.org>
36. Whiting PF, Rutjes AWS, Westwood ME, Mallett S, Deeks JJ, Reitsma JB et al. QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. *Ann Intern Med* 2011;**155**:529–536
37. Kim SH, Lilot M, Murphy LSL, Sidhu KS, Yu Z, Rinehart J et al. Accuracy of continuous noninvasive hemoglobin monitoring: a systematic review and meta-analysis. *Anesth Analg* 2014;**119**:332–346
38. Adel A, Awada W, Abdelhamid B, Omar H, Abd El Dayem O, Hasanin A et al. Accuracy and trending of non-invasive hemoglobin measurement during different volume and perfusion statuses. *J Clin Monit Comput* 2018;**32**:1025–1031
39. Applegate II RL, Applegate PM, Cannesson M, Peiris P, Ladlie BL, Torp K. Multicenter comparison of three intraoperative hemoglobin trend monitoring methods. *J Clin Monit Comput* 2020;**34**:883–892
40. Causey MW, Miller S, Foster A, Beekley A, Zenger D, Martin M. Validation of noninvasive hemoglobin measurements using the Masimo Radical-7 SpHb station. *Am J Surg* 2011;**201**:592–598
41. De Rosa RC. Accuracy of continuous monitoring of haemoglobin concentration after in-vivo adjustment. *Angiol Vasc Surg* 2020;**5**:1–6
42. Desebbe O, Faulcon C, Henaine R, Tran L, Koffel C, Delannoy B et al. Tissue hemoglobin monitoring is unable to follow variations of arterial hemoglobin during transitions from pulsatile to constant flow in cardiac surgery. *J Cardiothorac Vasc Anesth* 2014;**28**:668–673
43. Kayhan GE, Colak YZ, Sanli M, Ucar M, Toprak HI. Accuracy of non-invasive hemoglobin monitoring by pulse CO-oximeter during liver transplantation. *Minerva Anestesiol* 2017;**83**:485–492
44. Frasca D, Mounios H, Giraud B, Boisson M, Debaene B, Mimoz O. Continuous monitoring of haemoglobin concentration after in-vivo adjustment in patients undergoing surgery with blood loss. *Anaesthesia* 2015;**70**:803–809
45. Gill H, Navaratnarajah M, Tallach E, Fernandez E, Sury M. Assessment of a noninvasive hemoglobin monitor (Masimo SpHb) in infants and small children undergoing craniofacial surgery. *Pediatr Anesth* 2012;**22**:916–917
46. Gupta N, Kulkarni A, Bhargava A, Prakash A, Gupta N. Utility of non-invasive haemoglobin monitoring in oncology patients. *Indian J Anaesth* 2017;**61**:543
47. Jou F, Kurth C, Beckman E, Istaphanous G. Absolute and trend accuracy of continuous and noninvasive hemoglobin in pediatric surgery patients. *Anesth Analg* 2010;**110**:S1–S520
48. Kamel MM, Hasanin A, Nawar B, Mostafa M, Jacob VF, Elhadi H et al. Evaluation of noninvasive hemoglobin monitoring in children with congenital heart diseases. *Pediatr Anesth* 2020;**30**:571–576
49. Kapoor I, Mahajan C, Mamuliya R, Prabhakar H. Assessment of accuracy of continuous noninvasive versus invasive method of hemoglobin estimation in patients undergoing pituitary surgery. *J Neuroanaesth Crit Care* 2018;**5**:168–172
50. Khanna P, Rajagopalan V, Singh G, Prabhakar H. A comparison of non-invasive versus invasive methods of haemoglobin estimation in patients undergoing intracranial surgery. *South Afr J Anaesth Analg* 2014;**20**:160–163
51. Marques NR, Kramer GC, Voigt RB, Salter MG, Kinsky MP. Trending, accuracy, and precision of noninvasive hemoglobin monitoring during human hemorrhage and fixed crystalloid bolus. *Shock* 2015;**44**:45–49
52. Miller RD, Ward TA, Shiboski SC, Cohen NH. A comparison of three methods of hemoglobin monitoring in patients undergoing spine surgery. *Anesth Analg* 2011;**112**:858–863
53. Patino M, Schultz L, Hossain M, Moeller J, Mahmoud M, Gunter J et al. Trending and accuracy of noninvasive hemoglobin monitoring in pediatric perioperative patients. *Anesth Analg* 2014;**119**:920–925
54. Perez A, Bisbe E, Alvarez J, Lopez R, Fau M, Escolano F. Preliminary clinical evaluation of a continuous and noninvasive hemoglobin monitor (Masimo pulse CO-oximeter) in surgical patients. *Transfus Altern Transfus Med* 2009;**11**(s1):1–40
55. Saito J, Kitayama M, Oishi M, Kudo T, Sawada M, Hashimoto H et al. The accuracy of non-invasively continuous total hemoglobin measurement by pulse CO-oximetry undergoing acute normovolemic hemodilution and reinfusion of autologous blood. *J Anesth* 2015;**29**:29–34
56. Zeng R, Liu H, Li H, Xu X, Shangguan W, Li Y et al. Abstract PR282: accuracy of noninvasive and continuous hemoglobin measurements in Chinese children. *Anesth Analg* 2016;**123**:364–365
57. Divatia J, Pradhan S, Verma P. Haemoglobin estimation by non-invasive pulse co-oximetry or arterial blood co-oximetry are inferior to arterial hemocuetm estimation during intra-operative haemorrhage. *Anaesth Intensive Care* 2020;**48**:30
58. Gurskaia V, Pulkina O, Ivanov V, Savvina I. Intraoperative evaluation of non-invasive hemoglobin in children with craniocystosis. *Anesth Analg* 2021;**133**:1222
59. McNulty SE, Torjman M, Grodecki W, Marr A, Schieren H. A comparison of four bedside methods of hemoglobin assessment during cardiac surgery. *Anesth Analg* 1995;**81**:1197–1202
60. Patel KP, Hay GW, Cheteri MK, Holt DW. Hemoglobin test result variability and cost analysis of eight different analyzers during open heart surgery. *J Extra Corpor Technol* 2007;**39**:10–17
61. Richards NA, Boyce H, Yentis SM. Estimation of blood haemoglobin concentration using the HemoCue® during caesarean section: the effect of sampling site. *Int J Obstet Anesth* 2010;**19**:67–70
62. Sfez M, Desruelle P, Pennecot GF, Cohen-Bacrie P. [The importance of the preoperative measurement of hemoglobin concentration. Evaluation of a colorimetric method (Hemocue)]. *Cah Anesthesiol* 1991;**39**:247–251
63. Spielmann N, Mauch J, Madjdpour C, Schmutz M, Weiss M, Haas T. Accuracy and precision of hemoglobin point-of-care testing during major pediatric surgery. *Int J Lab Hematol* 2012;**34**:86–90

64. Ng WL, Short TG, Gunn KN, Fuge GS, Slon B. Accuracy and reliability of the i-STAT point-of-care device for the determination of haemoglobin concentration before and after major blood loss. *Anaesth Intensive Care* 2014;**42**:495–499
65. Carabini LM, Navarre WJ, Ault ML, Bebawy JF, Gupta DK. A comparison of hemoglobin measured by co-oximetry and central laboratory during major spine fusion surgery. *Anesth Analg* 2015;**120**:60–65
66. Despotis GJ, Saleem R, Bigham M, Barnes P. Clinical evaluation of a new, point-of-care hemocytometer. *Crit Care Med* 2000;**28**: 1185–1190
67. Jonsson H, Larsson A, Semenas E, Soderberg E, Lipcsey M. Point of care analysis of hematology in the operating theater—a prospective observational study of accuracy and feasibility. *Clin Lab* 2023;**69**:2
68. Altman DG, Bland JM. Measurement in medicine: the analysis of method comparison studies. *Statistician* 1983;**32**:307
69. Bland JM, Altman DG. Measuring agreement in method comparison studies. *Stat Methods Med Res* 1999;**8**:135–160
70. Johnston A, Bourner G, Martin T, McFarlane A, Good D, Padmore R et al. Guidance for quality control practices and precision goals for CBCs based on IQMH patterns-of-practice survey. *Int J Lab Hematol* 2019;**41**:15–22
71. Shabaninejad H, Ghadimi N, Sayehmiri K, Hosseini-fard H, Azarfarin R, Gorji HA. Comparison of invasive and noninvasive blood hemoglobin measurement in the operating room: a systematic review and meta-analysis. *J Anesth* 2019;**33**:441–453
72. Zortea T, da Silva Wizbicki DP, Madeira K, Ambrosio PG, de Souza ROB, Duraes ESM. [Noninvasive hemoglobin monitoring in clinical trials: a systematic review and meta-analysis]. *Braz J Anesthesiol* 2020;**70**:388–397
73. Baker L, Park L, Gilbert R, Ahn H, Martel A, Lenet T et al. Intraoperative red blood cell transfusion decision-making: a systematic review of guidelines. *Ann Surg* 2021;**274**:86–96